

# Magnetic zenith enhancement of HF radio-induced airglow production at HAARP

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[1] Airglow production at various beam positions relative to the magnetic field was investigated as part of an optics campaign at HAARP in February 2002. Strong emissions up to several hundred Rayleigh at 630.0 nm and more than 50 R at 557.7 nm were produced in a small spot approximately 6° in diameter located near the magnetic zenith when the transmitter beam was directed up the magnetic field. This effect was observed hundreds of times over a wide range of frequencies and ionospheric conditions. The spot at HAARP appears on average just equatorward of the nominal magnetic field direction, deflects somewhat toward the beam center when the beam is scanned, and varies slightly in size with transmitter frequency. Red-to-green ratios as low as 3 were observed, with both wavelengths showing significant onset delay. Identifiable enhancements in red-line emission were produced down to 2 MW ERP in a power ramp experiment. **INDEX TERMS:** 0310 Atmospheric Composition and Structure: Airglow and aurora; 2403 Ionosphere: Active experiments; 2483 Ionosphere: Wave/particle interactions; 2487 Ionosphere: Wave propagation (6934); 2494 Ionosphere: Instruments and techniques. **Citation:** Pedersen, T. R., M. McCarrick, E. Gerken, C. Selcher, D. Sentman, H. C. Carlson, and A. Gurevich, Magnetic zenith enhancement of HF radio-induced airglow production at HAARP, *Geophys. Res. Lett.*, 30(4), 1169, doi:10.1029/2002GL016096, 2003.

## 1. Introduction

[2] Production of airglow by HF radio wave excitation was considered difficult at high latitudes until the most recent solar maximum when a number of observations have been made in both Scandinavia and Alaska [Brandstrom *et al.*, 1999; Kosch *et al.*, 2000; Leyser *et al.*, 2000; Pedersen and Carlson, 2001; Gustavsson *et al.*, 2001]. In the Leyser *et al.* [2000] and Kosch *et al.* [2000] observations the airglow region was reported as a localized enhancement much smaller than the beam diameter. Kosch *et al.* [2000] found the airglow region to be displaced away from the beam center toward the magnetic equator, with maxima

located near the Spitze angle and magnetic zenith. In the first airglow observations from the High Frequency Active Auroral Research Program (HAARP) facility in Alaska, Pedersen and Carlson [2001] reported a preferential brightening near magnetic zenith outside the half power limits of the vertical transmitter beam. Based on the EISCAT and HAARP results, a series of experiments was formulated for a March 2001 campaign at HAARP to attempt excitation of airglow at a variety of transmitter beam launch angles relative to the magnetic field. Bright aurora and excessive absorption limited the results from the March 2001 launch angle experiments, but airglow produced during vertical incidence heating was observed in two distinct forms: beam-filling diffuse airglow and a discrete spot located outside the vertical beam near the magnetic zenith [Pedersen *et al.*, 2001]. Gurevich *et al.* [2001] considered the EISCAT and HAARP observations and proposed a theory in which self-focusing by small-scale striations could produce a bright spot along the magnetic meridian within an extended beam.

[3] The HAARP launch angle experiments were attempted again under more favorable conditions in February 2002 as part of a dedicated optics campaign. In this paper we describe the dramatic and reproducible enhancements of artificial airglow generated during the February 2002 experiments when the transmitter beam was directed up the magnetic field line and present several fundamental characteristics of the airglow enhancements as determined by direct observation.

## 2. Observations

[4] The HAARP optical campaign was carried out from February 1–21, 2002 at the HAARP facility near Gakona, Alaska (62.39°N 145.15°W). Several optical instruments were employed, including the HAARP imager [Pedersen and Carlson, 2001], which took all-sky images at 630.0, 557.7, 427.8, and 777.4 nm. The launch angle experiments were first run on February 3, and experiments on subsequent days were revised to take advantage of the high levels of airglow seen when transmitting up the magnetic field, allowing strong airglow to be observed on all campaign nights with sufficiently clear skies.

[5] From 4 to 5 UT on February 3 the HAARP transmitter was operated at full power in ordinary (O) mode polarization with the beam rotated in a 10-minute repeating conical scan pattern composed of 30 s dwells at each of 20 beam positions 15° off zenith and spaced 18° in azimuth. The beam swept from N toward E then S and W, and became approximately parallel to the magnetic field at about 6 minutes into each scan. The first scan was carried out at

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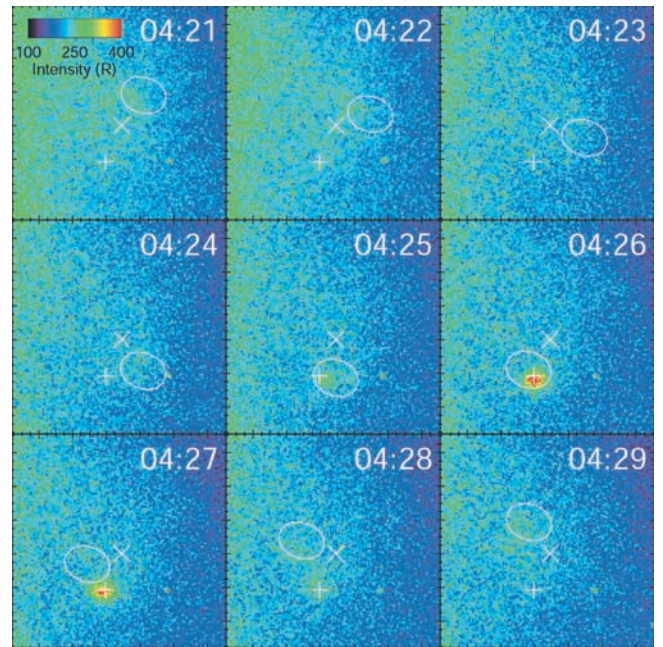
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6.8 MHz, but  $f_{oF2}$  was slightly below the transmitter frequency at 6.5 MHz, and no significant airglow was seen. The transmitter frequency was reduced to 5.8 MHz for the second cycle, bringing it below  $f_{oF2}$ , which had dropped slightly to 6.2 MHz. This time a bright spot of enhanced 630.0 nm emission about 150 R above background appeared near the magnetic zenith as the beam swept through and gradually faded after the beam passed. The spot reappeared on three following scans at 5.8 MHz from 04:20 to 04:50 UT, with peak intensities up to 250 R above background, and again on a fifth scan starting at 04:50 when the frequency was reduced to 4.8 MHz following a decline in  $f_{oF2}$ .

[6] Figure 1 shows a time series of calibrated 630.0 nm image data from the HAARP imager at 1 minute intervals for the scan cycle from 04:20 to 04:30 UT. Each panel shows the central region of a 630.0 nm all-sky image. True zenith is marked with an “X”, and the direction antiparallel to the magnetic field vector is indicated with a plus. A white oval shows the  $-3\text{dB}$  power contour of the transmitter beam. The last remnants of twilight are visible as an east-west gradient in the background level. Weak beam-filling airglow enhancements on the order of 10 R can just be made out trailing the beam around much of the circle, especially at 24, 28, and 29 minutes after 04:00, but are dwarfed by the large enhancement which appeared as the beam traveled past the magnetic zenith point. The first indication of the enhancement in this figure appears at 04:25 as a region of slightly brighter emissions just east of the magnetic zenith point as the beam approaches. At 04:26 the enhancement peaks at more than 200 R above the background and is centered slightly south of the nominal magnetic zenith. At 04:27 the beam has moved on and the bright spot has begun to fade. The obvious lag between the beam position and airglow intensity is partly the result of the images being taken near the start of each beam dwell period and partly due to actual delays in the emission response at 630.0 nm as discussed by *Bernhardt et al.* [1989a], *Pedersen and Carlson* [2001] and others. At 04:28 the last vestiges of the spot appear as a region of reduced enhancement centered slightly NW of the magnetic zenith. The same general behavior was observed in each conical scan, namely first appearance slightly E of magnetic zenith, motion following the beam to the W, then dissipation slightly to the NW of magnetic zenith. After the conical scans, the transmitter began a series of 3 min on 2 min off cycles pointing at locations spaced  $15^\circ$  in elevation along the magnetic meridian. With the exception of a few cases when the F-layer critical frequency dropped below the transmitter frequency, airglow enhancements were observed each time the beam was directed up the magnetic field. Secondary enhancements in the magnetic field direction were also seen from beam positions  $15^\circ\text{N}$  and  $\text{S}$  of magnetic zenith at 3.3 MHz where the beam has a relatively large size ( $\sim 27^\circ\text{N-S}$ , full width at half maximum (FWHM)).

[7] On the night of February 5, 2002, the transmitter beam was scanned numerous times in elevation along the magnetic meridian through the magnetic zenith from  $90^\circ$  to  $63^\circ$  elevation over the course of 10 min., then across the magnetic zenith in azimuth for another 10 min. Figure 2 shows magnetic N-S profiles through 630.0 nm images centered near the spot location for this night as a function



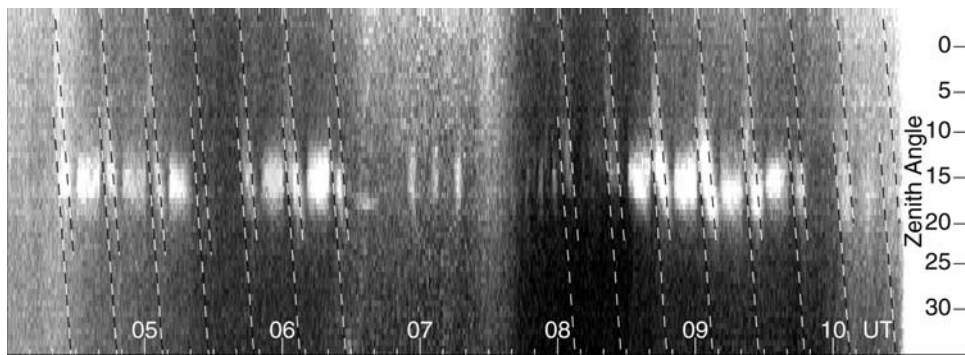
**Figure 1.** HAARP imager data from a conical scan at  $15^\circ$  from vertical. The vertical is marked with an “X” and magnetic zenith with a “+”.

of universal time. Brightness ranges from 150 R (black) to 500 R (white). Zenith angles are marked on the right hand side of the figure, and the beam half-power limits during the elevation scans are indicated by dashed lines. As the beam scanned in elevation toward the average location of the spot, airglow enhancements were observed to form at a slightly higher elevation compared to the average position and then follow the beam somewhat toward lower elevations, making the bright spot appear slightly stretched and tilted in this composite plot. As on the night of February 3, emissions were produced almost every time the beam was directed up the magnetic field, the most notable exception being 05:20–05:40 UT when  $f_{oF2}$  dropped below the transmitter frequency.

[8] Over the course of the campaign, airglow enhancements of 50 R or more in the magnetic zenith were observed in almost 1,200 individual red-line images on 8 different nights. Although significant structure within the spot was observed on some occasions, the typical appearance was of a nearly circular region averaging  $7.2^\circ\text{E-W}$  and  $6.4^\circ\text{N-S}$ , FWHM. The average location of the emission centroid was  $74.6^\circ$  el.,  $204.4^\circ$  az. The size of the spot was observed to decrease slightly with increasing transmitter frequency, which ranged from 3.3 to 7.8 MHz over the course of the experiments. The intensity of the spot exceeded 300 R above background at times and was observed over a wide range of  $f_{oF2}$  values from under 4 MHz to approximately 10 MHz, at transmitter frequencies as much as 4 MHz below  $f_{oF2}$ . Emission intensity was largely independent of either transmitter or ionospheric critical frequency. The brightest emissions had a slight tendency to occur very near  $f_{oF2}$ , but all emissions cut off sharply at about 0.5 MHz above  $f_{oF2}$ .

[9] Prior to the February 2002 campaign only minimal levels of green line emission at 557.7 nm ( $\sim 5$  R) had been





**Figure 2.** Time history of 630.0 nm image sections along the magnetic meridian ( $204^\circ$  az) during elevation and azimuth scans through the spot on February 5, 2002. Beam half-power limits are marked with dashed lines during elevation scan periods.

detected at HAARP [Pedersen *et al.*, 2001]. Directing transmitter energy up the magnetic field, however, allowed generation of green line emissions of 10–30 R or more on most clear nights of the campaign. Green line intensities appeared to be positively correlated with transmitter ERP, occurring preferentially at higher transmitter frequencies, whereas red line enhancements generally saturated at about 300 R above background even at higher frequencies and ERP.

[10] Figure 3 shows intensities within the magnetic zenith spot during one of the most intense green-line events, which occurred on February 13, 2002. The transmitter was operated at 7.8 MHz with an ERP of  $\sim 160$  MW. Red-line enhancements of more than 200 R and green emissions close to 70 R were observed over 5 separate transmitter pulses (indicated by dashed lines), with a red-green ratio of approximately 3:1. Comparison of red and green images simultaneous to within 12 s showed no detectable difference in spot size or structure at the two wavelengths for much of this period, although significant structure in green line emissions was occasionally observed with narrower field of view instruments.

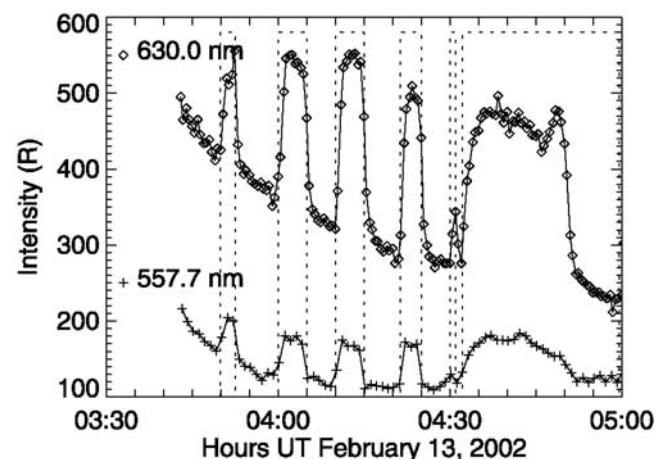
[11] The data points in Figure 3 are from 2 red line exposures made at 0 and 24 s after each minute, with one 557.7 nm exposure in between at 12 s. The transmitter turned on exactly on the minute at 04:00 and 04:10 but was started 3 s ahead and 18 s behind the minute during the shorter cycles at 03:50 and 04:21, respectively. A transmitter problem produced a false start prior to the long heating period begun at 04:32:12. The temporal dependence of the red line emissions in Figure 3 is generally consistent with the long lifetime of the  $O(^1D)$  state and is similar to earlier observations from HAARP. The 557.7 nm data for the first three periods, however, show the green line emission level to have reached only about a third of the maximum value in the exposures begun 12 s into the minute, representing a large delay relative to the short ( $\sim 0.7$  sec) lifetime of the source excited state.

[12] The high efficiency of airglow production and apparent saturation at 630.0 nm when transmitter power was directed up the magnetic field suggested investigation of the power threshold at which the effects begin. A power ramping mode was devised in which transmitter power was gradually increased from 10% to 100% of full power (960 kW) and then dropped back down again. Following the continuous

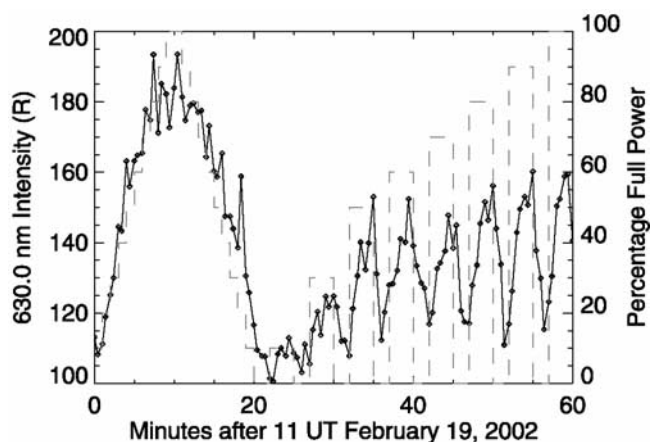
power ramp, individual on/off cycles (3 min on 2 off) were carried out at 10, 30, 50, 60, 70, 80, 90, and 100 percent of full power. Figure 4 shows the results of one such experiment, carried out from 11:00–12:00 UT on February 19, 2002, at a transmitter frequency of 3.3 MHz ( $\sim 20$  MW ERP at full power). The red line emission gradually rose to  $\sim 200$  R above the background as the transmitter reached full power at  $\sim 10$  minutes into the experiment, and then dropped gradually down to the background level as power decreased. The discrete on-off cycles following the continuous power ramp showed distinct airglow peaks at each level, although the maximum apparently reached saturation at about 50% full power during this portion of the experiment. Of greatest interest is the peak of  $\sim 10$  R at the 10% power level, representing enhancement of the airglow at an ERP of only 2 MW.

### 3. Discussion

[13] Previous reports of discrete spots of artificial airglow at high latitudes such as Kosch *et al.* [2000] and Pedersen and Carlson [2001] discussed the appearance of enhanced emissions near the magnetic zenith in terms of a “displacement” away from the nominal beam pointing direction. The



**Figure 3.** Time history of emission intensities within the spot at 630.0 nm (diamond) and 557.7 nm (plus) on 13 Feb. 2002. The dashed line indicates transmitter on-off cycles.



**Figure 4.** Emission intensity at 630.0 nm during a power ramp experiment on February 19, 2002. The dashed gray line indicates transmitter power as a percentage of full ERP, which was approximately 20 MW at the 3.3 MHz frequency used.

large number of observations from the February 2002 HAARP campaign made utilizing both scanning and static beams intentionally directed along the magnetic field, however, make it very clear that the enhanced conversion of RF power in the magnetic zenith is a consistently present effect depending directly on propagation geometry, and is active even at extremely low ERP. The observed excitation of the spot away from the beam center and small displacements of the emission region toward the beam center in such a way as to increase the power density within the emission region are consistent with self-focusing behavior exploiting the geometry of the magnetic field. The average location of the spot center at  $74.6^\circ$  el.,  $204.4^\circ$  az. is slightly equatorward of the nominal direction of the magnetic field at ground level ( $204.9^\circ$  az  $75.9^\circ$  el), but is coincident with the direction parallel to the local magnetic field vector in the spot location at  $F$ -region altitude ( $203.5^\circ$  az  $74.6^\circ$  el) to within the resolution of the image data. The increase in spot size with transmitter wavelength is also consistent with the general concept of self-focusing, as longer waves are refracted more by any radial density gradient, allowing the spot to capture rays at larger angles of incidence relative to the magnetic field.

[14] The February 2002 HAARP observations have several implications for the theory of HF radio-induced airglow generation. The self-focusing characteristics and extreme sensitivity of the magnetic zenith spot provide general support for the Gurevich *et al.* [2001] striation theory, which has been expanded upon in consideration of these new results [Gurevich *et al.*, 2002]. Observation of intense green line emissions and low red/green ratios is a strong, if not definitive, indication of a sizeable suprathermal contribution to the airglow excitation, contrasting with the thermal interpretation of earlier airglow observations at HAARP [Pedersen and Carlson, 2001]. Airglow observations over a

wide range of transmitter and ionospheric frequencies provide many test cases on both sides of the 5–6 MHz  $f_{oF2}$  threshold discussed by these authors as the divide between thermal and suprathermal excitation regimes. The large apparent delay in green line excitation, while reminiscent of the lag expected from thermal time constants and inconsistent with direct wave excitation of the short-lived O ( $^1S$ ) state, is perhaps more likely to be an indication of larger-scale transport and re-arrangement of the plasma required under a self-focusing process such as that of Gurevich *et al.* [2002] to produce the high power densities favoring suprathermal excitation.

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